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Physics with "2nd Generation" Pixel Detectors

Pixel Detector Evolution

- First generation (developed in early 90's):
  - minimal circuitry in pixel (pre-amp, discriminator, trigger coincidence, flip-flop)
  - common threshold
  - ~1 μm technology
  - full matrix (slow) read-out
  - used by CERN fixed-target heavy ion experiments (Omega3/LHC1 chip, 50x500 μm^2 pixels) and Delphi at LEP for forward tracking (330x330 μm^2 pixels)

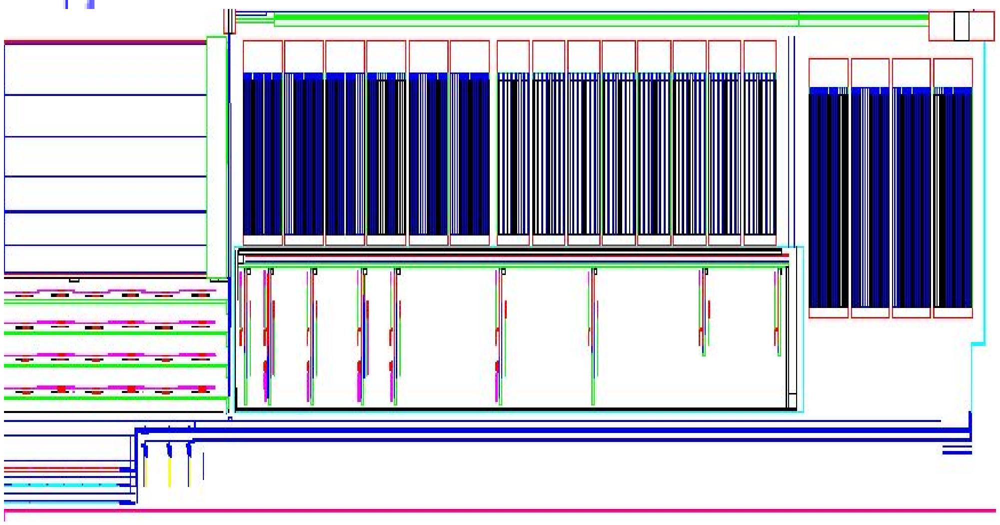
Pixel Detector Evolution

- Second generation (developed since the mid-90's):
  - complex circuitry in pixel (pre-amp, individually adjustable discriminator, pulse height measurement, read-out logic)
  - (rad-hard) deep sub-micron technology
  - sparse (fast) read-out
  - radiation-hard sensors, electronics and infrastructure
  - to be used by:
    - the ATLAS and CMS collider experiments at LHC
    - the BTeV B-Physics experiment at FNAL
    - the ALICE heavy-ion experiment at LHC

Need for Pixel Detectors

- Events at (near) future colliders are characterized by:
  - high rates (~20 p-p events per bunch crossing at LHC design luminosity)
  - high particle multiplicities (up to 8000 charged particles per unit of rapidity in heavy ion collisions at LHC)
- Pixel vertex detectors are needed because of their:
  - excellent 3-D position resolution (≈10 μm)
  - excellent 2-track resolution (≈100 μm)
  - good timing resolution (better than one bunch crossing)
  - low occupancy

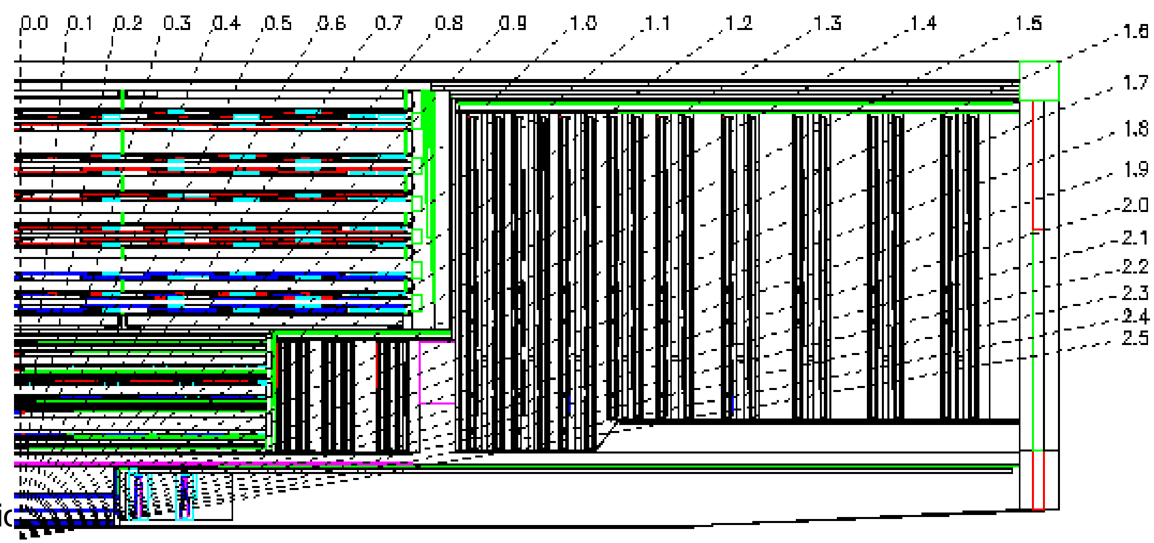
ATLAS & CMS: tracking



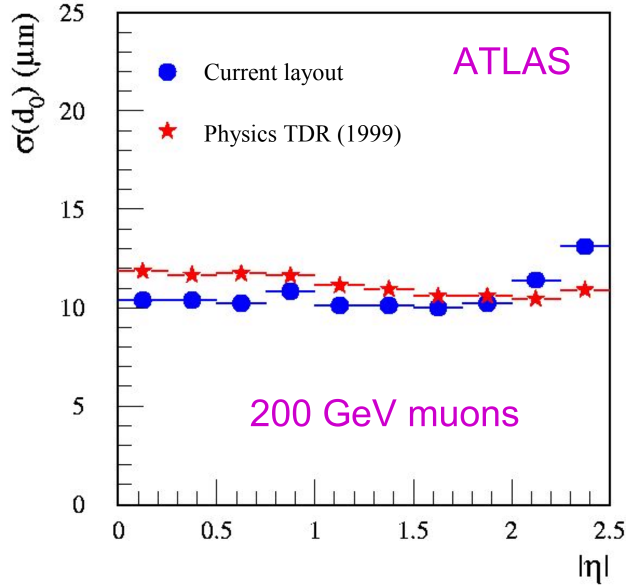
ATLAS Inner Detector:

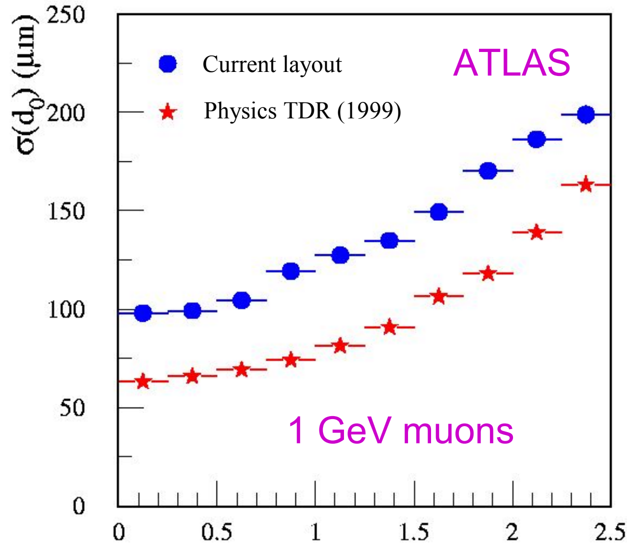
- 2/3 layers of Pixel Detectors
- 4 layers of Silicon Microstrips
- Transition Radiation Tracker (~35 points/track + TR info for electron identification)

- CMS Tracker:
  - 2/3 layers of Pixels
  - 10 layers of Silicon Microstrips (4 Inner, 6 Outer)



ATLAS & CMS: tracking



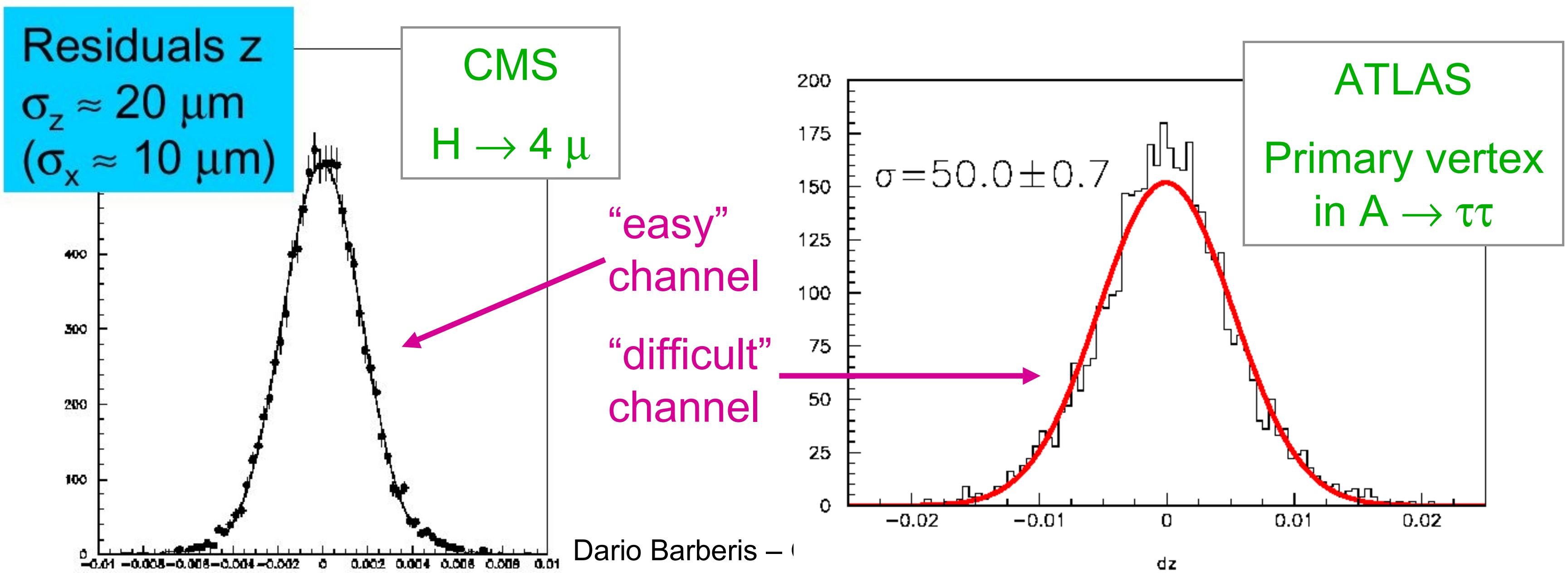


- ATLAS and CMS are THICK trackers:
  - each pixel layer contributes >2% X_0
  - plus global support and cooling structures and thermal/EMI screens
- The impact parameter resolution depends strongly on:
  - radius of innermost pixel layer
  - thickness of pixel layers
  - radius and thickness of beam pipe
- Example:
  - effect of (1 cm) increase of beam pipe and B-layer radius in ATLAS: now

$$\sigma(d_0) \approx 10 \oplus \frac{98}{p_T \sqrt{\sin\vartheta}}$$

ATLAS & CMS: vertexing

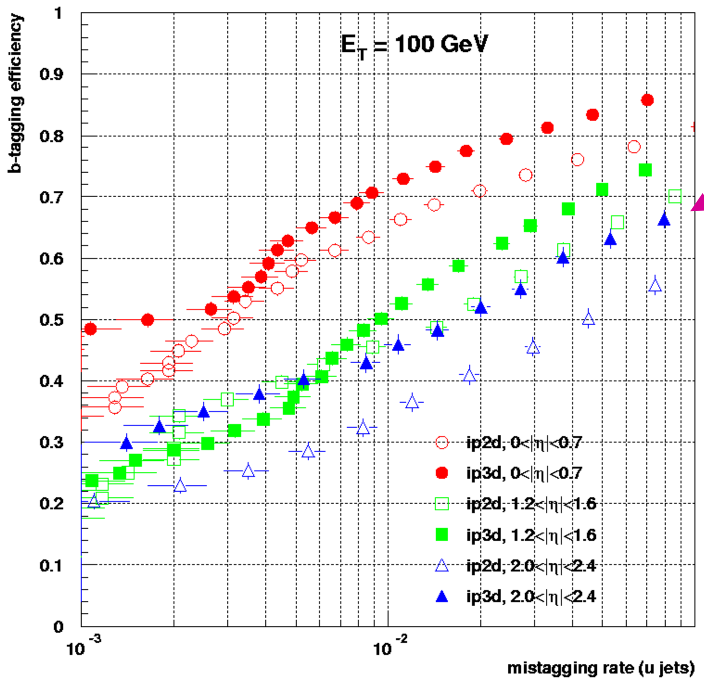
- At LHC design luminosity ~20 interactions occur per beam crossing
- They are spread with $\sigma(z) = 5.6$ cm
- Need identification of the primary vertex of the hard (triggered) interaction and reconstruction of any secondary vertices in jets
- Pixel detectors allow primary vertex reconstruction with $\sigma(z) < 50$ µm



ATLAS & CMS: b tagging

- Several algorithms tried by CMS and ATLAS, based on:
  - impact parameter (track counting and jet probability)
  - secondary vertex reconstruction
  - decay length

- Typical performance for both experiments:
  - average: $\varepsilon(u) \sim 1\%$ for $\varepsilon(b) = 60\%$ for "interesting" jet p_T range ($50 < p_T < 130$ GeV) and all rapidities
  - best: $\varepsilon(u) \sim 0.2\%$ for $\varepsilon(b) = 50\%$ for $p_T \sim 100$ GeV and central rapidity

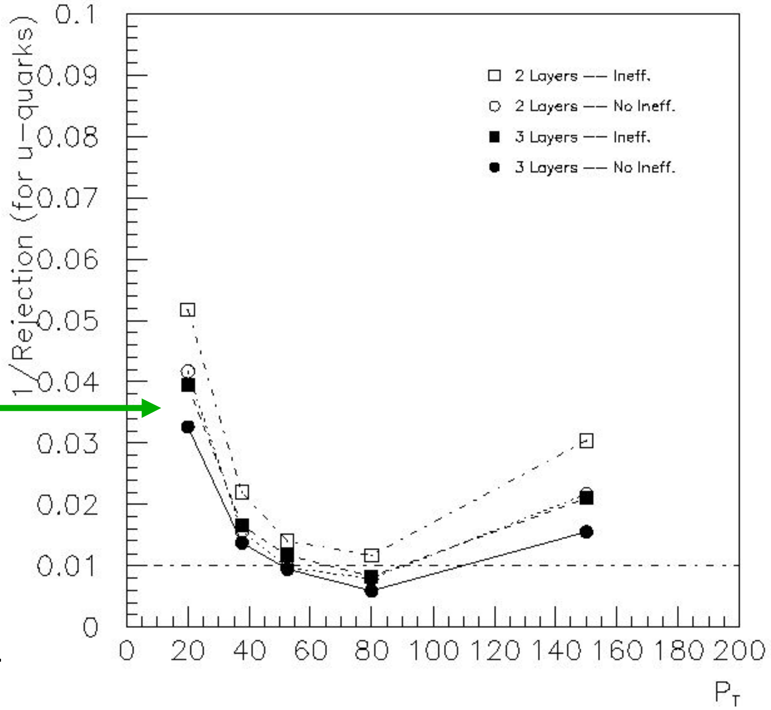


CMS:

2-D & 3-D I.P. prob.: $\varepsilon(b)$ vs $\varepsilon(u)$

ATLAS:

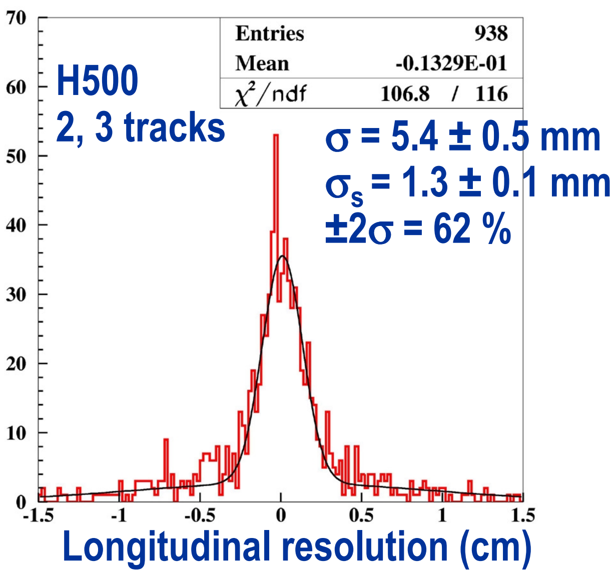
2-D I.P. prob.: $\varepsilon(u)$ vs p_T (all η)

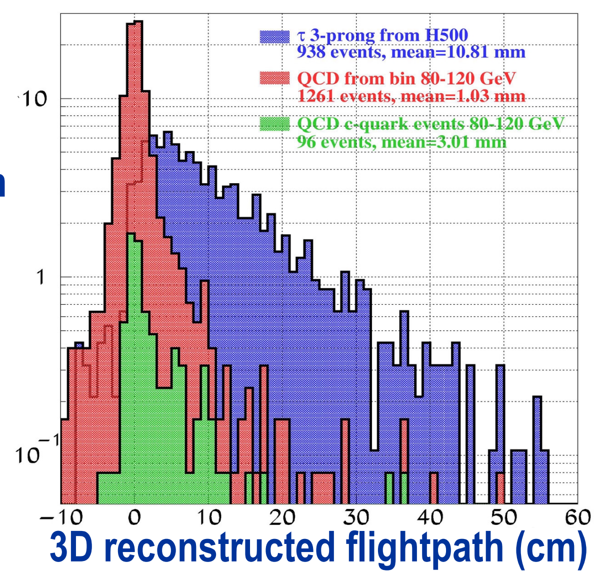


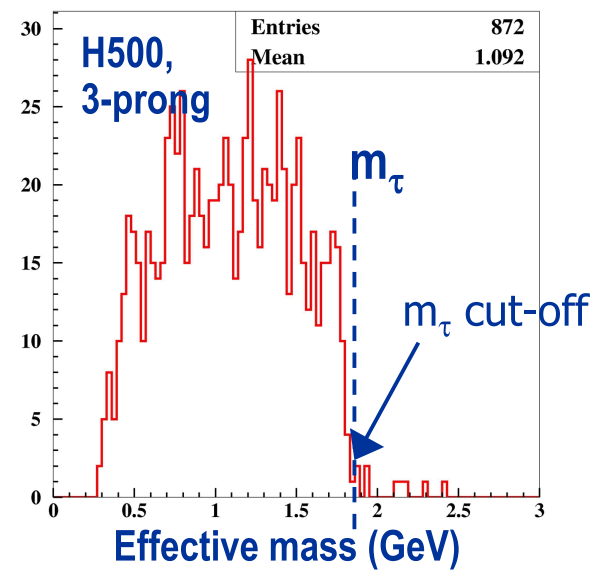
ATLAS & CMS: hadronic τ reconstruction

• If 3-prong τ events can be used in addition to 1-prong τ decays, a factor of 1.7 of signal events are gained for Higgs and Supersymmetry

• 3-prong decay vertices can be reconstructed with sufficient precision:





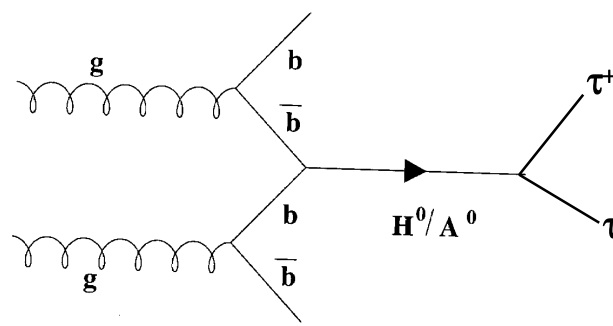


• **MSSM: 5 Higgs bosons: h, H, A, H^+,H^-.**

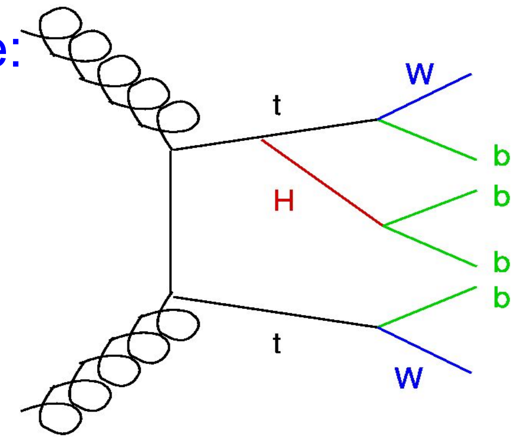
• **At tree-level boson masses are functions of m_A (CP-odd Higgs boson) and tan(β).**

• **LEP: M_A > 91.9 GeV and tan(β) > 2.4 (95% CL).**

• **M_A in "few 100 GeV" range for reasonable parameters**

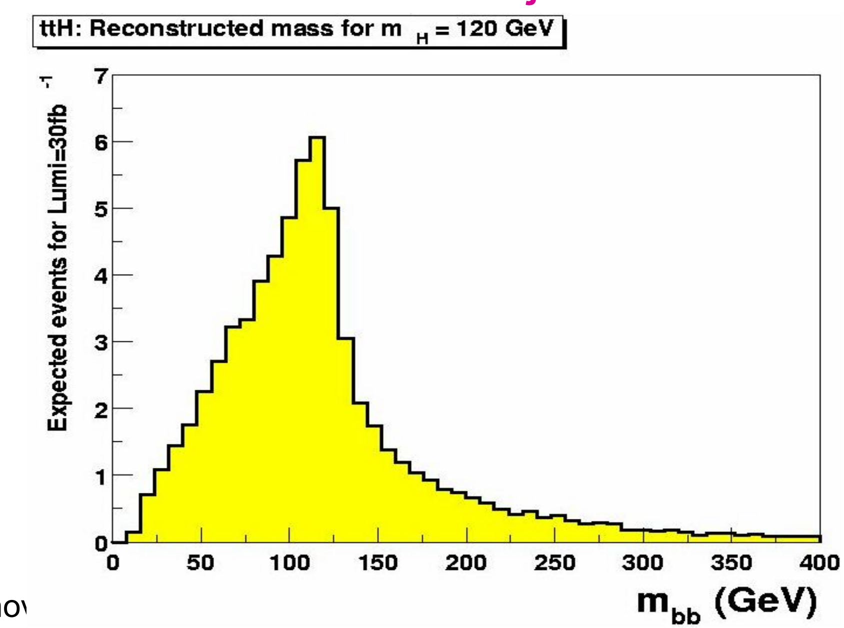


ATLAS & CMS: Higgs



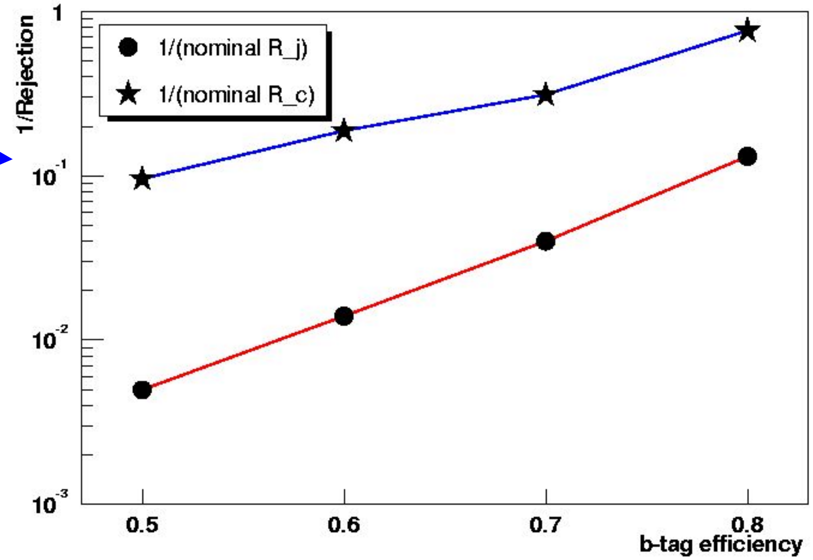
- Let's take the channel $gg \rightarrow t\bar{t}H \rightarrow t\bar{t}b\bar{b}$ as example:
- Very sensitive to b-tag performance (4 b-jets)
- Needs full reconstruction of both top decays to suppress combinatorial background
- Remaining backgrounds:
  - irreducible: direct $t\bar{t}b\bar{b}$ production (QCD & EW)
  - reducible: $t\bar{t}jj$ and $t\bar{t}jb$ with misidentification of non-b jets

Process	σ (pb)	σ x BR (pb)
ttH(120)	0.55	0.11
ttjj, ttjb	473	138
ttbb (QCD)	8.6	2.5
ttbb (EW)	0.90	0.26

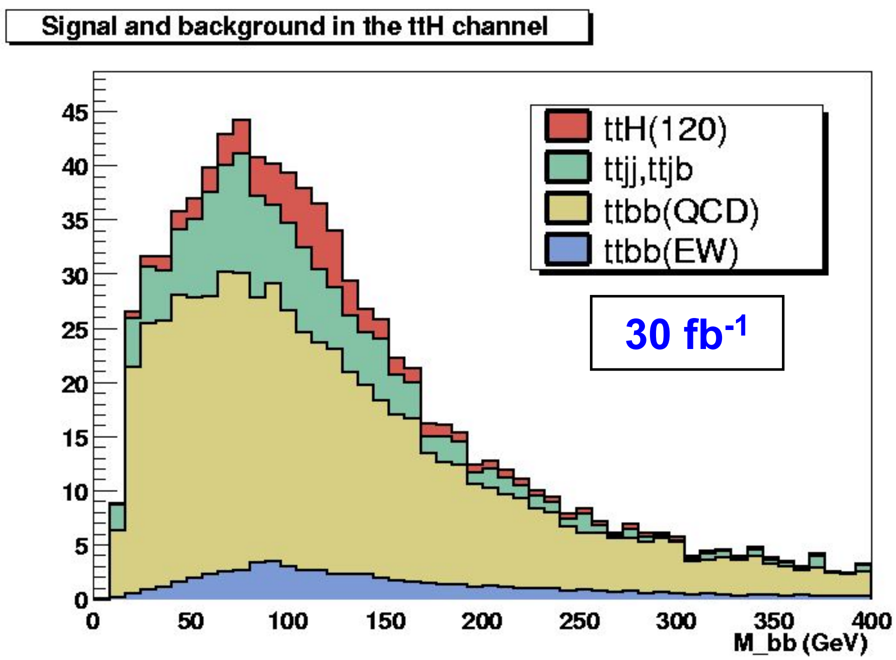


Associated Higgs production: the $t\bar{t}H$ channel

- Take the $\varepsilon(b)$ = 60% point on the efficiency vs rejection curve:



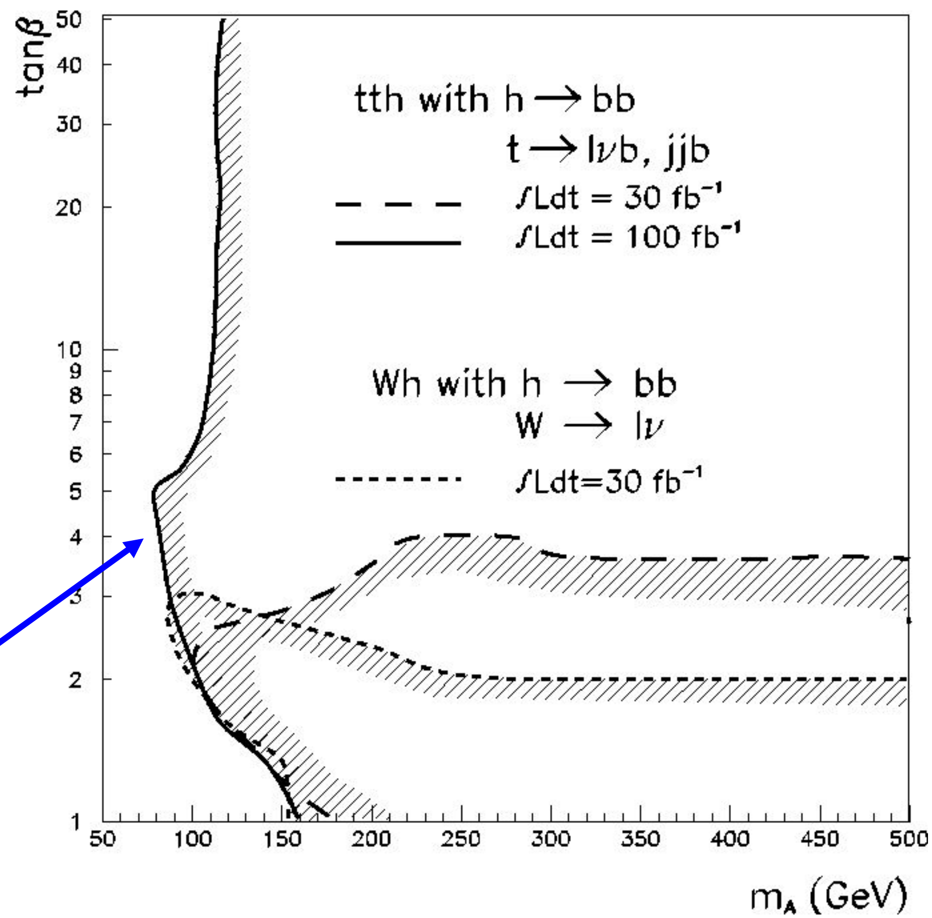
- Get average rejection ~100 for light quarks and ~7 for charm
- Use p_T and η dependence
- Produce the bb mass spectrum:



- The background is dominated by irreducible QCD ttbb events (b-tag performance already good enough!)
- The statistical significance is $S/\sqrt{B} \sim 3.5$ for an integrated luminosity of 60 fb^{-1}
(3 years at luminosity 2×10^{33} $cm^{-2}s^{-1}$)

MSSM: the t$\bar{t}$h channel

- In the Minimal Supersymmetric Standard Model, the tth (h $\rightarrow$ bb) channel can have a “reasonable” cross-section
- Cross-section depends on MSSM parameters
- Larger than Standard Model ttH (H $\rightarrow$ bb) production for most parameter space
- Significance larger than 5σ (“discovery threshold”) over most of parameter space for 100 fb^{-1} of integrated luminosity



5σ discovery contour in the (m_A,tanβ) plane for MSSM tth, h$\rightarrow$bb

ATLAS & CMS: Supersymmetry

- Quite a few Susy final states with b's and/or τ's
- Good b/τ reconstruction allows
  - full or partial reconstruction of Susy events
  - determination of some sparticle masses
- Susy rates dominated (depending on Susy model) by production of
  - $\tilde{g}\tilde{g}$
  - $\tilde{g}\tilde{q}$
  - $\tilde{q}\tilde{q}$
- Lightest Susy particle ($\tilde{\chi}^0{}_1$) is
  - stable
  - neutral
  - weakly interacting (escapes the detector)
  - gives "missing energy"
- Classical signature for Susy production:
  - Excess of final states with
    - missing energy ($\not{E}$)
    - several hard central jets arising from $\tilde{q}\tilde{q}$, $\tilde{q}\tilde{g}$, ...

Supersymmetry: the $h \to b\bar{b}$ channel

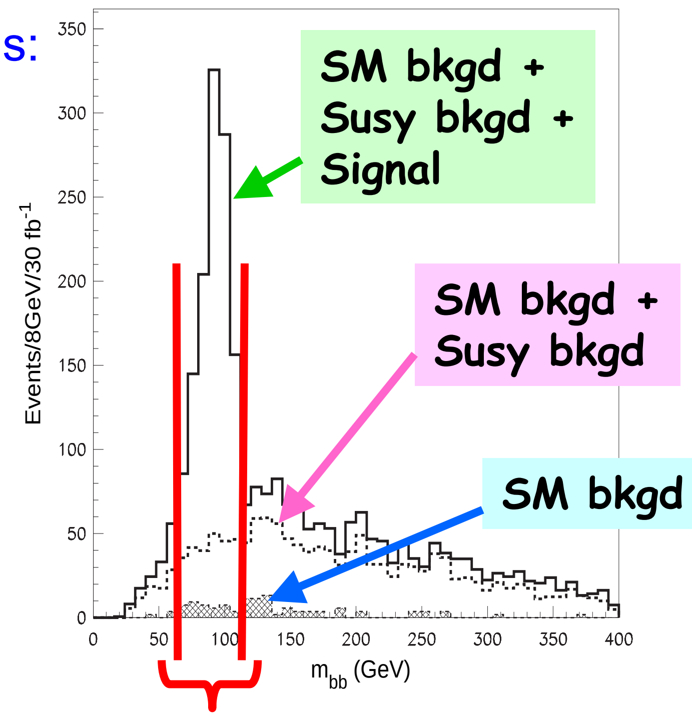
- Example: using b reconstruction in mSugra models:
  - $h^0 \to b\, b$ in cascade decays
- Decay chain:

$\tilde{q}_L \to \tilde{\chi}^0_2\, \tilde{q}$ (~30%)

$\quad \hookrightarrow h\, \tilde{\chi}^0_1$ (70 to 90%)

$\quad\quad \hookrightarrow b\, \bar{b}$ (80 to 90%)

- Analysis procedure:
  - Get clean sample of $h \to bb$
  - Reconstruction of $h \to bb$ decay
  - Get m_h
  - Partial reconstruction of $\tilde{q}_L \to \tilde{\chi}^0_2\, q \to h\, \tilde{\chi}^0_1\, q$
  - Get invariant mass of jbb system
    - sensitive to $m_{\tilde{q}_L}$
  - Get p_T distribution of 2^{nd} hardest jet
    - sensitive to $m_{\tilde{q}_L}$ or $m_{\tilde{q}_R}$



Invariant mass of bb system:

Events with M_{bb} within $\pm$ 25 GeV of peak:

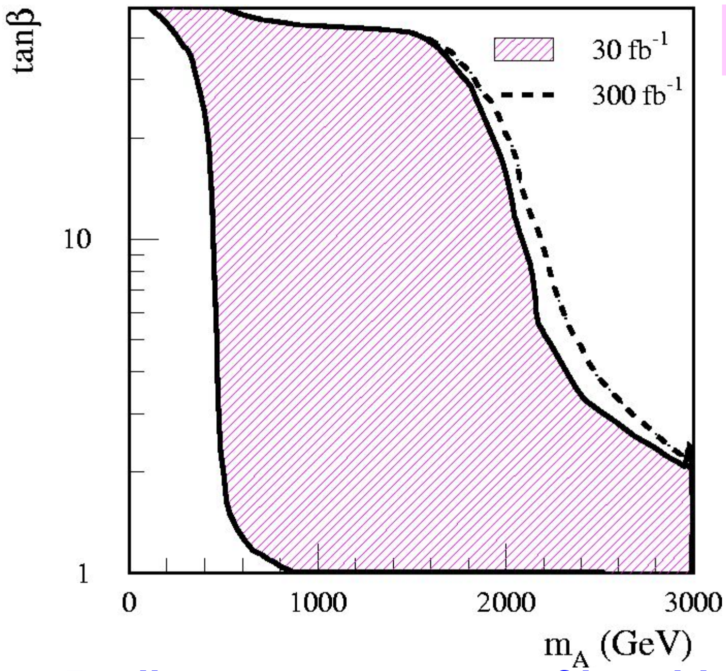
SM bkgd < 10% of signal

Susy bkgd < 20% of signal

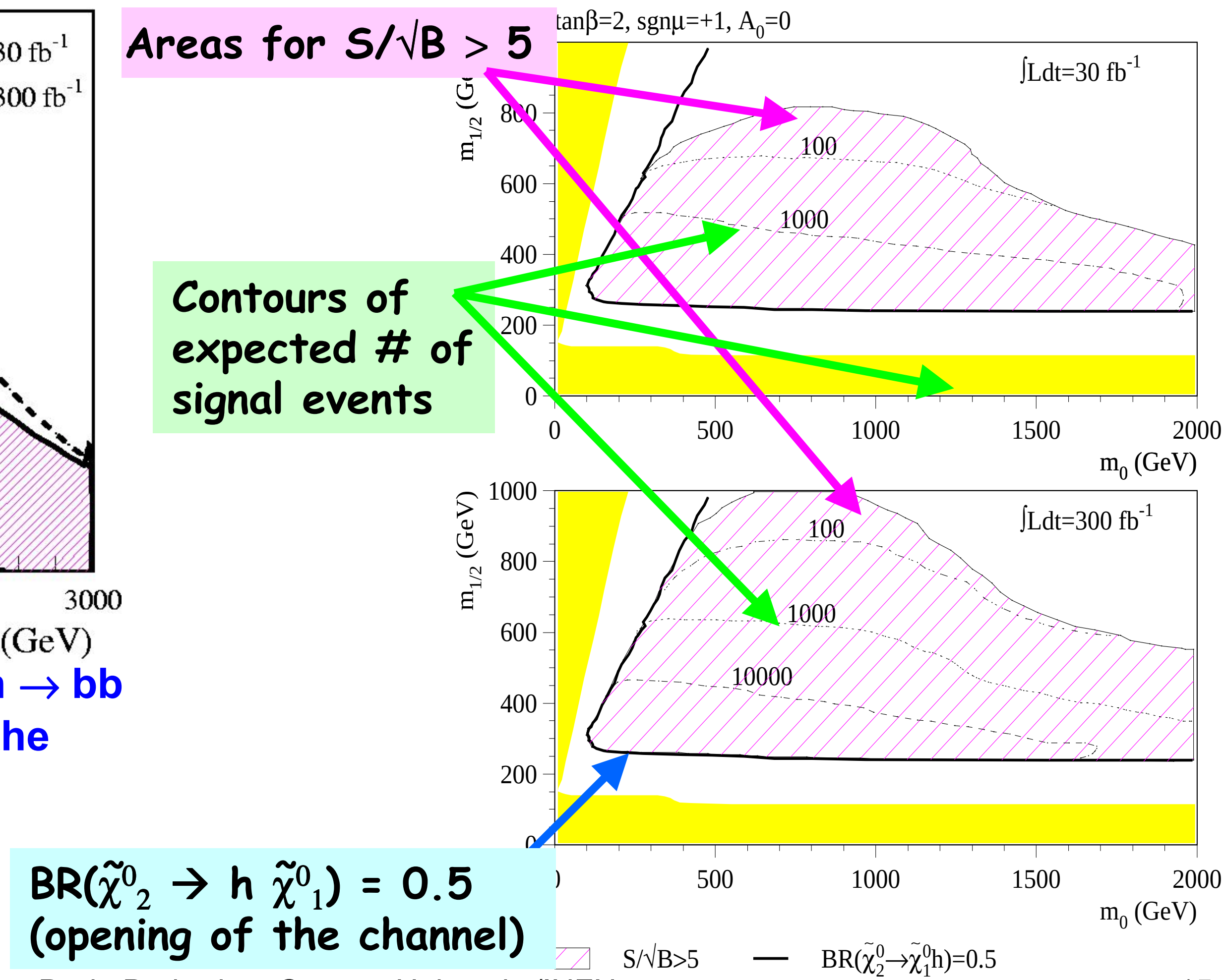
Fit of peak: Δm_h ~ 1 GeV

Observability of the $h \to b\bar{b}$ channel

Observability 5σ-contours of $h \to bb$ from SUSY cascade:



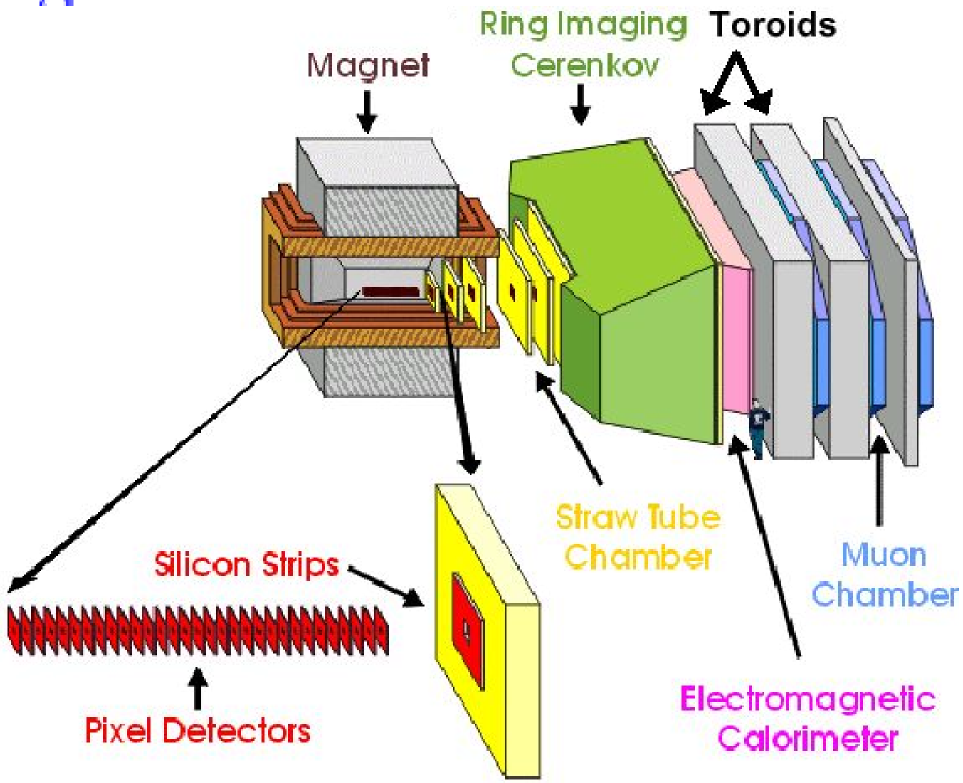
5σ discovery contours of $h \to bb$ from SUSY cascade in the (m_A,tanβ) plane



B Physics: Goals

- Measure:
  - CP violation in B decays
  - B_s mixing
  - rare B decay rates
- Look for “forbidden” decays
- Measure precisely Standard Model parameters
- Test for inconsistencies of the Standard Model
- Search for Physics beyond the Standard Model

B Physics: BTeV



- CM energy: 2 TeV
- Luminosity: 2 10^{32} $cm^{-2}s^{-1}$
- Integ. lumin.: 2 fb^{-1}/year

- 30 pixel detector stations
- Level-1 pixel track trigger:
  - track reconstruction
  - primary vertex reconstr.
  - displaced track selection
- Particle identification:
  - RICH (liquid+gas radiators)
- Photon detection:
  - $PbWO_4$ calorimeter
- Muon measurements:
  - toroids, proportional tubes, trigger

B Physics: BTeV

- Precision measurements of CKM parameters:
  - $\sigma(\sin(2\beta)) \sim 0.017$ after 1 year using $B^0 \to J/\psi\, K^0_s$
  - sign(β) determined using $B^0 \to J/\psi\, K^0$, $K^0 \to \pi \ell \nu$
  - Asymmetry of $B^0 \to \pi^+\pi^-$ measured to ± 0.030 in 1 year
  - Penguin contribution determined by Dalitz plot analysis of $B^0 \to \rho\pi \to \pi^+\pi^-\pi^0$, sensitive to both $\sin(2\alpha)$ and $\cos(2\alpha)$: $\sigma(\alpha) < 4^o$ in 2 years
  - $\sigma(\gamma) \sim 4\text{-}8^o$ in 1 year using $B_s \to D_s^+K^-$, $B^- \to D^0K^-$, $B^- \to K_s\pi^-$, $B^0 \to K^+\pi^-$, $B^0 \to \pi^+\pi^-$ and $B_s \to K^+K^-$
  - $\sigma(\chi) \sim 0.024$ in 1 year (but expect $\chi \sim 0.03$!!!) using $B_s \to J/\psi\, \eta \to \ell^+\ell^-\gamma\gamma$ and $B_s \to J/\psi\, \eta' \to \ell^+\ell\ \ \rho^0\gamma$

B Physics: BTeV

- Consistency checks of the Standard Model:
  - is it true that $\alpha + \beta + \gamma = 180^o$?
  - check of χ: $\sin(\chi) = \lambda^2 \dfrac{\sin(\beta)\sin(\gamma)}{\sin(\beta+\gamma)}$
  - measure Δm_s and compare with Standard Model global fit (~17 ps^{-1})
- New Physics can also produce high(er) rates of flavour-changing neutral current decays:
  - look at $B \to K \ell^+\ell^-$ and $B \to K^* \ell^+\ell^-$ decays (Dalitz plots and $\ell^+\ell^-$ mass spectrum)

B Physics: ATLAS & CMS

- ATLAS and CMS are well equipped for broad B-Physics programme
- Beauty trigger strategies will be adapted according to luminosity conditions: di-lepton L1 triggers at higher luminosities, single-lepton at lower luminosities, followed by track reconstruction
- In CP violation the main emphasis will be on underlying mechanisms and evidence of new physics. ATLAS and CMS can measure (in 1 year at low luminosity) $\sin(2\beta)$ with precision similar to BTeV
- Sensitivity to Δm_s goes far beyond SM expectations. All parameters of the decay $B_s \rightarrow J/\psi\,\varphi$ can be measured with 1% precision (12% for $\Delta\Gamma_s$)
- Rare decays $B \rightarrow \mu\mu$ can be measured also at nominal LHC luminosity (10^{34} $cm^{-2}s^{-1}$). Will also measure branching ratio of $B_s \rightarrow \mu\mu$ which is in SM of order 10^{-9}. Precision measurements will be done for $B \rightarrow K^*\mu\mu$.
- Beauty production and correlations at central LHC collisions can be measured for QCD tests

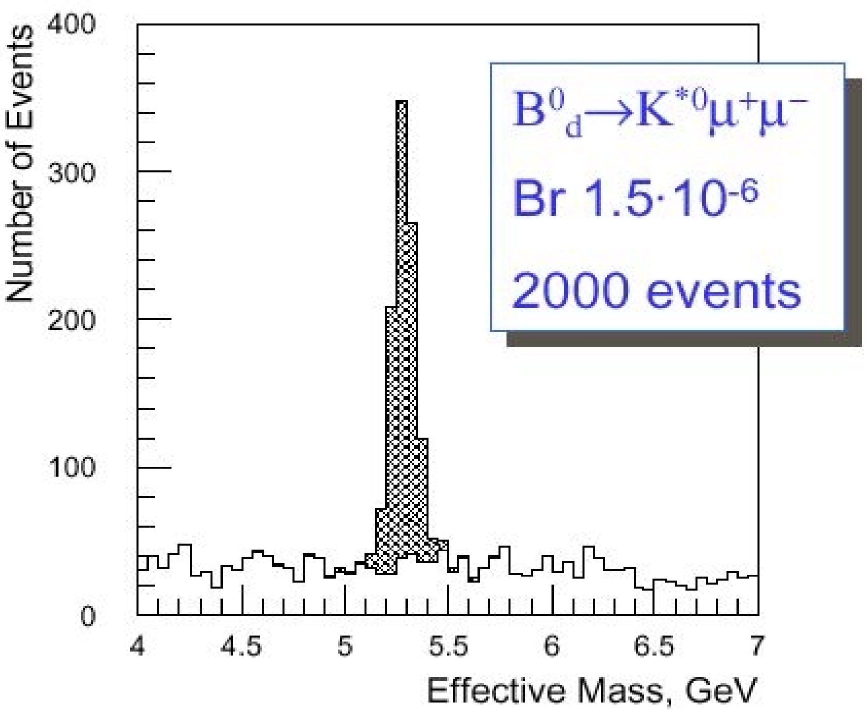
B Physics: ATLAS & CMS

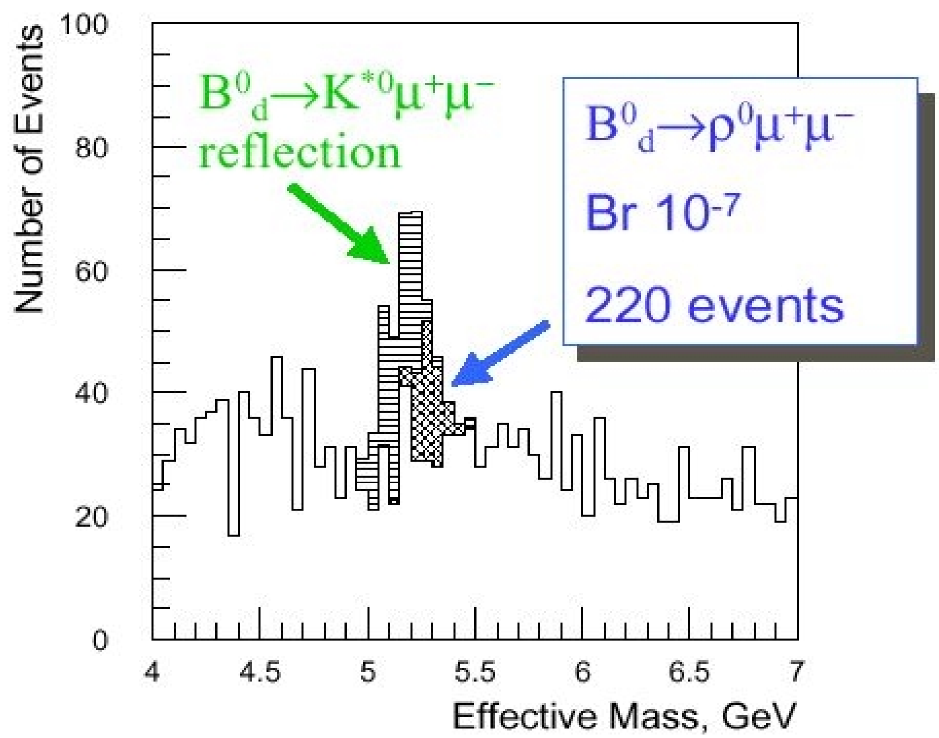
Rare decays: $B^0_{d,s} \to \mu^+ \mu^- X$

$B^0_d \to K^{0*}\mu^+\mu^-$, $B^0_d \to \rho^0\mu^+\mu$, $B^0_s \to \phi^0\mu^+\mu^-$

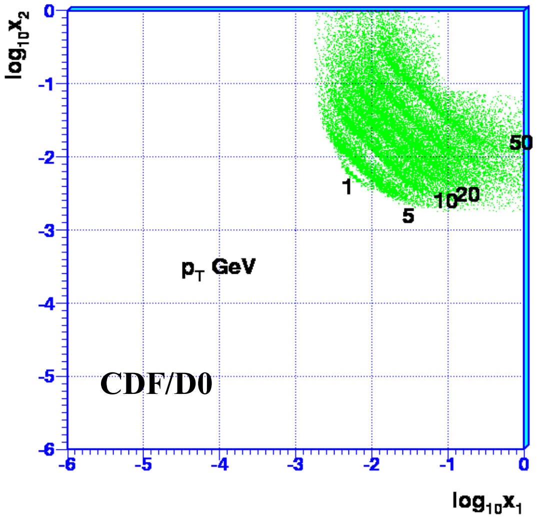
$BR(B^0_d \to \rho^0\mu^+\mu^-)/BR(B^0_d \to K^{0*}\mu^+\mu^-) = k_d\, |V_{td}/V_{ts}|^2$

Could be determined to ~15% after 30 fb^{-1}



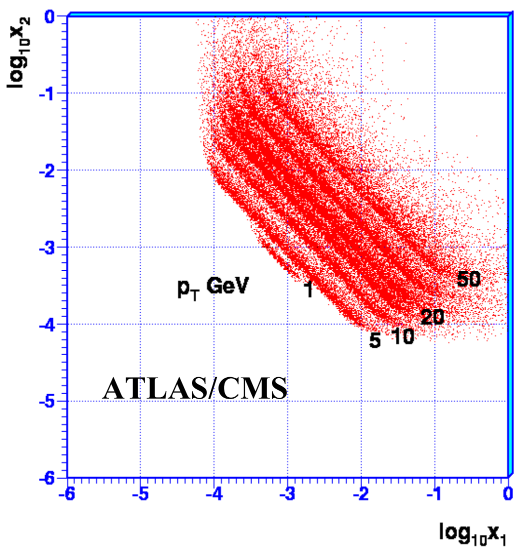


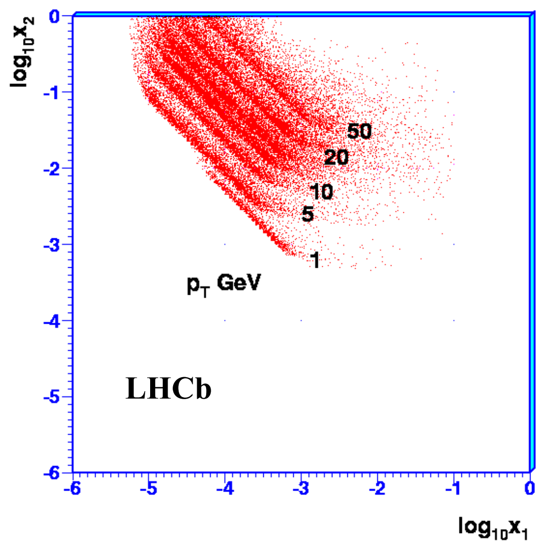
B Physics: b production cross-section

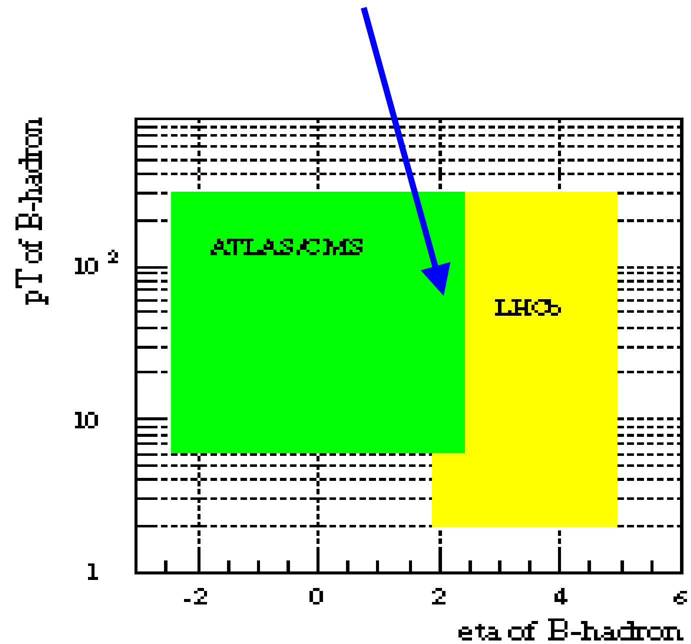


Bjorken-x region: one of B's in detector volume: BTeV and LHCb most sensitive to knowledge of structure functions at very low x

Common part of phase space: opportunity for normalization checks in Beauty cross-section measurements

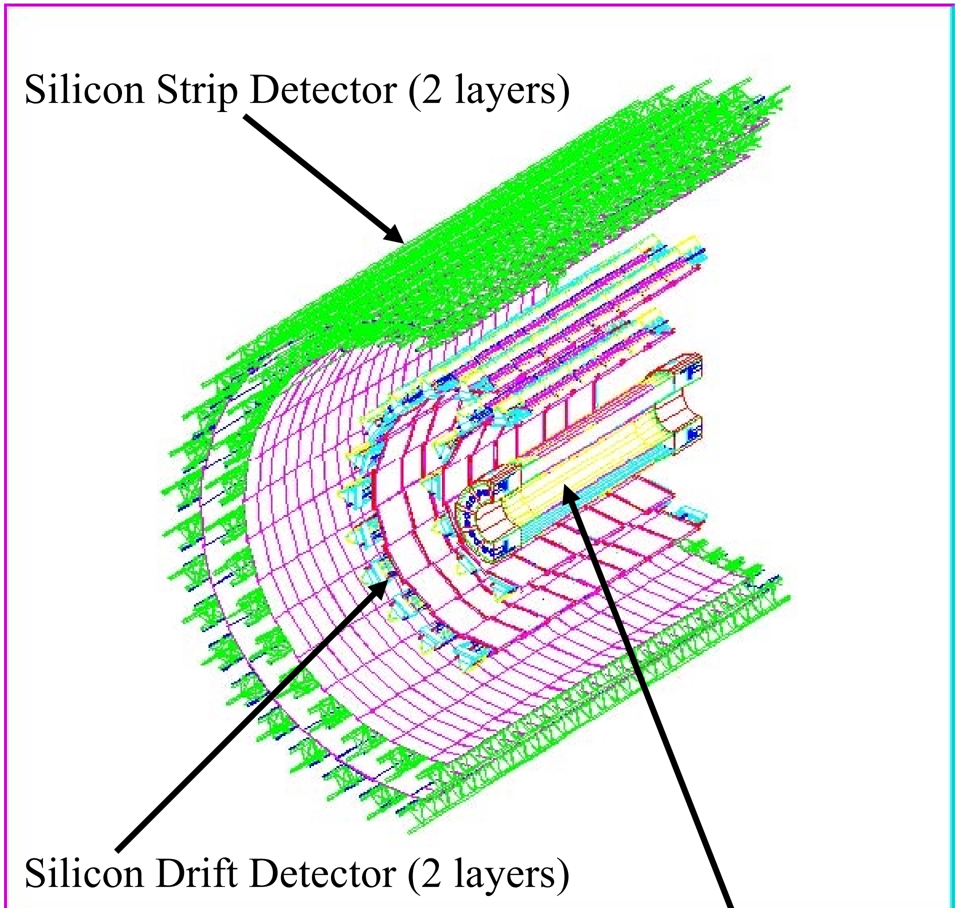


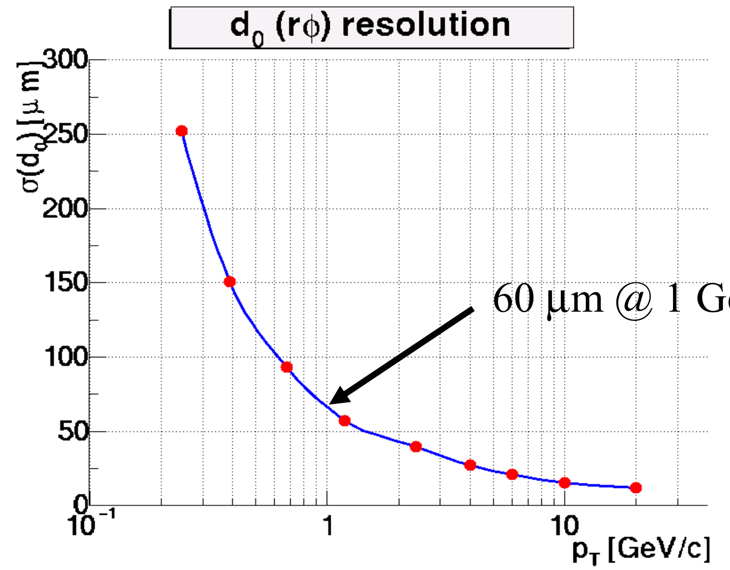


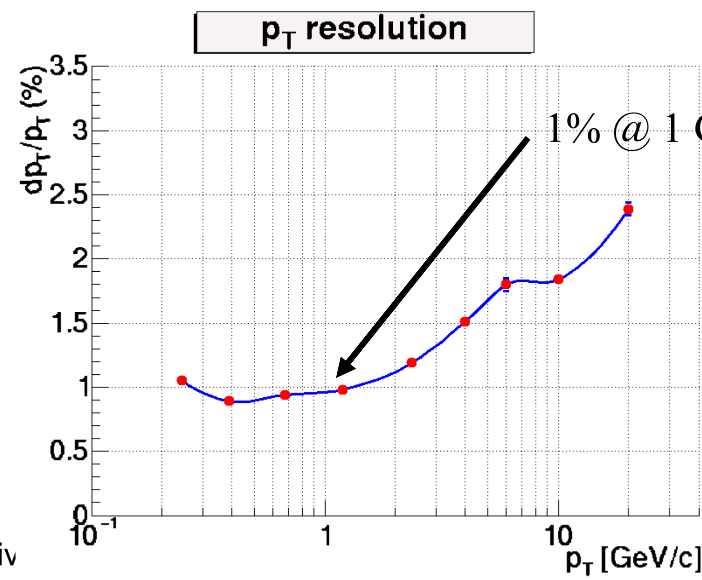


Heavy Ion Physics: ALICE

Inner Tracking System



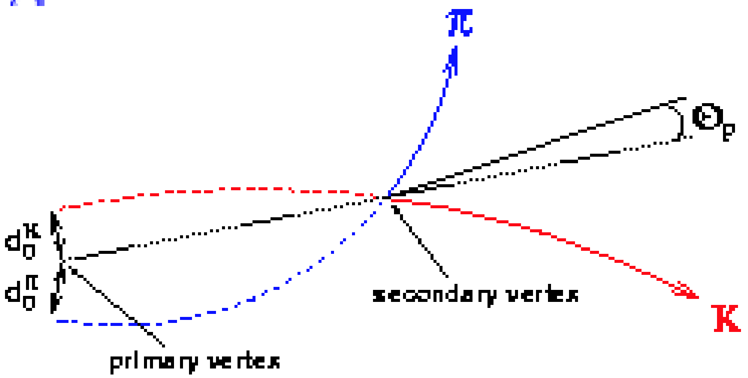


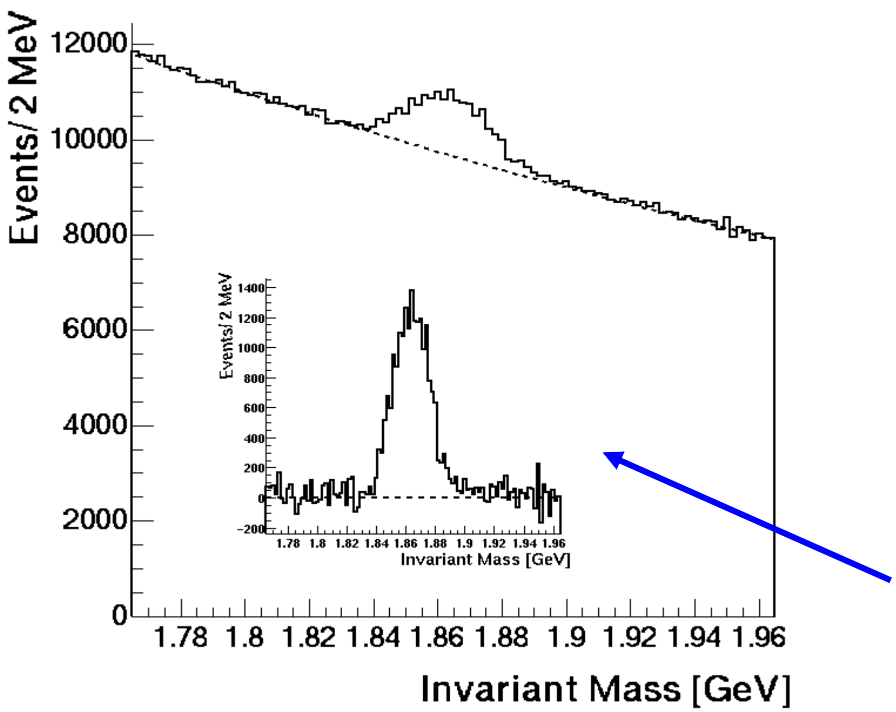


Heavy Ion Physics: ALICE

- open c, b production: natural normalization for quarkonia (J/ψ, Υ) production
- B mesons source of non-prompt J/ψ
- sensitive to conditions of initial reaction phase
  - structure functions
  - “thermal” charm?
- but parton energy loss in deconfined matter alters momentum spectrum
- window on hard processes

Heavy Ion Physics: ALICE

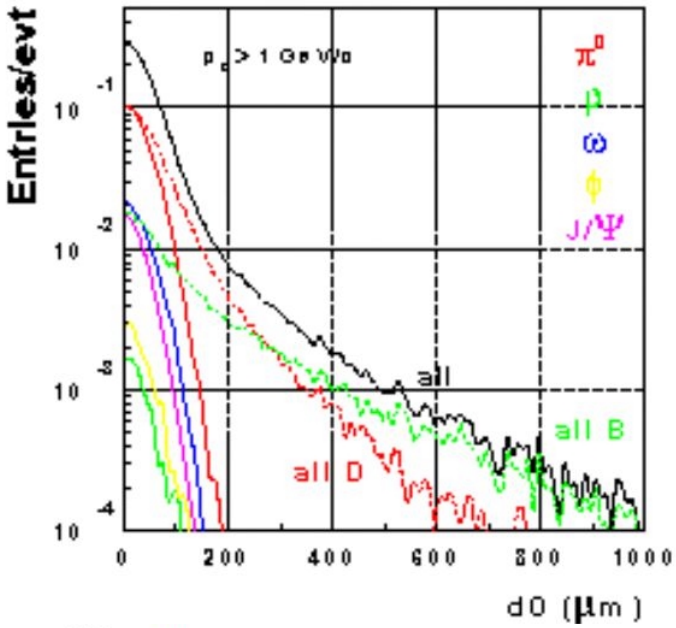


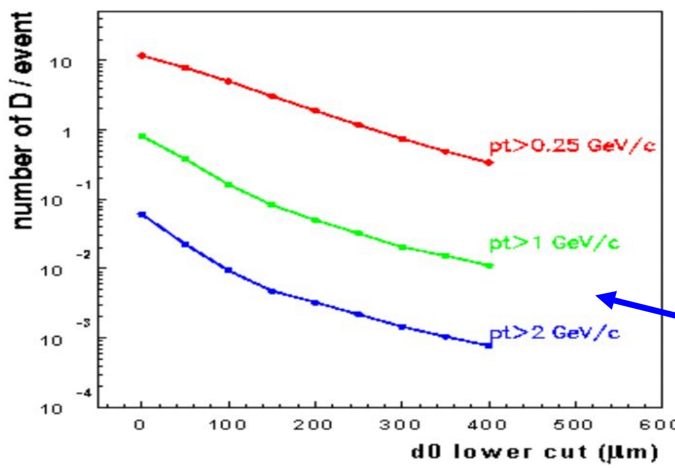


- Exclusive charm hadronic decays: full reconstruction of decay topology
- Identification strategy:
  - combinatorial association (initial S/B ~ 10^{-6})
  - selection on high transverse impact parameter track pairs
  - collinearity of D momentum vector with primary vertex
- D^0 signal after 15 days of data taking: significance ~ 35

Heavy Ion Physics: ALICE

Semileptonic decays: selection on impact parameter of electrons (TRD)

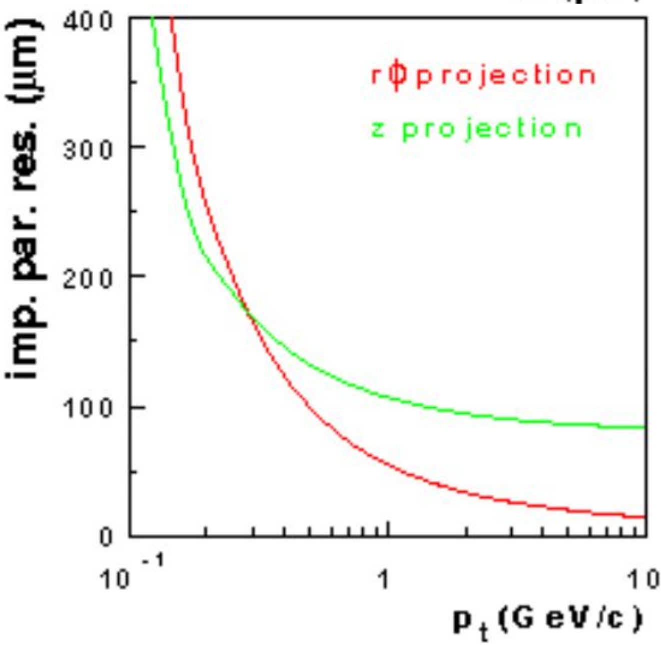




Semileptonic charm yield for p_T > 1 GeV and d_0 > 100 μm:

S/(S+B) = 0.5

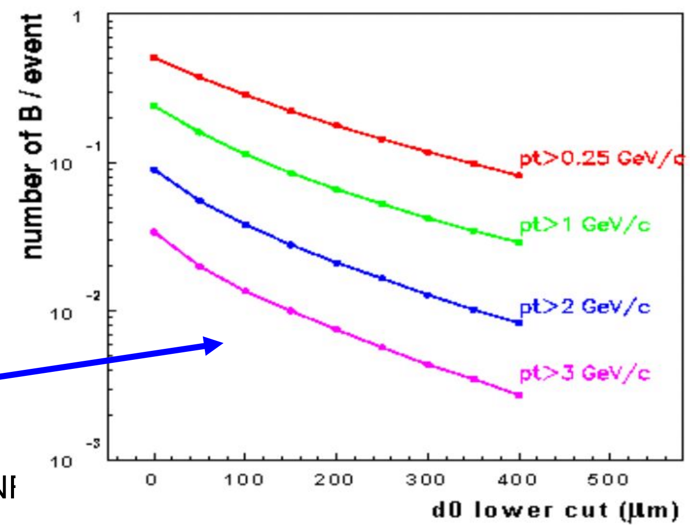
S ~ 1.5%



Semileptonic beauty yield for p_T > 3 GeV and d_0 > 100 μm:

S/(S+B) = 0.9

S ~ 2%



Conclusions and Outlook

- **Pixel vertex detectors are essential for the forthcoming generation of experiments, for the reconstruction of:**
  - ✓ **primary interaction points (separation of multiple interactions)**
  - ✓ **b and τ decay vertices (QCD, Higgs and SUSY Physics)**
  - ✓ **tracks in high-density environments (high luminosity or heavy ions)**
- **Performance adequate for the time being, but main limitations to physics performance are due to:**
  - ✓ **material effects (hadronic interactions, photon conversions)**
  - ✓ **data rate and dead time at high luminosity (data loss)**
  - ✓ **yield and efficiency? radiation damage?**
- **Ideas for R&D for 3rd generation detectors already around!**